Multipoint Observations of ^{3}He-rich Solar Energetic Particle Events using STEREO and ACE

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Abstract. **Multipoint observations of ^{3}He-rich solar energetic particle (SEP) events using instruments on the ACE and STEREO have been made over the period January 2007 to May 2009, during which the separation between the two STEREO spacecraft in heliolongitude increased from $\sim$0.5° to 95°. Relatively quiet conditions on the Sun allowed identification of probable source regions. In one event (4 November 2008), ions were detected at STEREO-B and ACE and electrons at all three spacecraft. The longitudinal distributions of energetic particles from ^{3}He-rich SEP events are discussed and compared with results from previous studies.**

Keywords**: solar energetic particles, ^{3}He-rich SEP events, particle transport**

I. Introduction

In the prevailing model of ^{3}He-rich solar energetic particle (SEP) events, acceleration of ions and electrons is powered by magnetic reconnection at the site of a solar flare. When the reconnection involves some open magnetic field lines, energetic particles can escape into the heliosphere. It is expected that the longitudinal distribution of these escaping particles should be relatively narrow due to the localized nature of the source region. This expectation is supported by studies comparing single-point observations of ^{3}He-rich SEP events at 1 AU with the locations of the associated flare sites on the Sun [1], [2], as well as by a study combining He isotope data from Helios-1 & -2 and ISEE-3 [3]. However, another investigation using Helios and near-Earth data [4] showed that electrons from impulsive SEP events frequently have much broader longitudinal distributions. One of the goals of the NASA STEREO mission is to make multipoint in situ measurements of SEP events while imaging their source regions in order to better understand acceleration and transport processes in these events.

The period from STEREO commissioning in January 2007 through May 2009 when the two STEREO spacecraft had each separated from one another by $>$90° in heliolongitude was characterized by very low solar activity, and few ^{3}He-rich SEP events were detected by spacecraft at 1 AU. However, because of the quiet Sun and the low SEP event rate, associations between observations of the same event at multiple spacecraft and with activity imaged on the Sun could be made with little risk of confusion.

In this paper we report observations of ^{3}He-rich SEP events made using the LET, SEPT, and SIT instruments on STEREO-A and -B and the SIS, EPAM, and ULEIS instruments on ACE. Imaging data from the SECCHI instruments on STEREO and the LASCO and EUVI instruments on SOHO as well as radio burst data from the WAVES instruments on both STEREO and WIND were used to associate the in situ observations with activity on the Sun. These instruments are described in detail in [5], [6], and [7].

II. ^{3}He-rich SEP Events

Events were selected based on the observation of a measurable increase of ^{3}He intensity in the energy range 2.3–3.8 MeV/nuc in the LET instrument on STEREO-A and/or -B. The other data sources mentioned above were then checked for additional detections of these events or of their solar sources. The two STEREO spacecraft carry identical instrument payloads and thus the species and energy coverage as well as the sensitivity are essentially the same. The ACE instrument designs differ from those on STEREO and these differences need to be taken into account in comparing observations.

A. The 24 January 2007 Event

The largest of the observed ^{3}He-rich events occurred on 24 January 2007 when the two STEREO spacecraft were near Earth, essentially collocated (longitudinal separation $\sim$0.5°) with one another and with ACE.

Although large in comparison with the other events discussed in this paper, the 24 January 2007 event was rather small in comparison to many of the ^{3}He-rich SEP events observed closer to solar maximum. For example, the ^{3}He fluence at 5 MeV/nuc in the 24 January 2007 event was a factor $\sim$20 less than in the extensively studied event of 9 September 1998 [9], which was far from the largest ^{3}He-rich event of solar cycle 23.

This 24 January event originated from active region 10939, which was located at $\sim$S04W60 and produced a number of B-class x-ray flares. Thus the observing spacecraft were well-connected to the flare site by a nominal Parker-spiral magnetic field. Type III radio bursts, indicating the escape of low-energy electrons from the Sun, were observed in conjunction with these events, and higher energy electrons were detected by the spacecraft at 1 AU.

Figure 1 compares the energy spectra of ^{3}He and ^{4}He measured by the STEREO/LET instruments and by the combination of ULEIS and SIS on ACE. There is good agreement between the spectra measured using the STEREO/LETs and ACE/SIS in the 5–10 MeV/nuc energy interval where their measurements overlap. Extrapolation of the STEREO energy spectra to below 1 MeV/nuc also yields reasonable agreement with measurements from ACE/ULEIS. The ^{3}He/^{4}He ratio, measured to be $\sim$1 above $\sim$2 MeV/nuc, decreases towards lower energies and reaches a value of $\sim$0.1 at 0.3 MeV/nuc. Events of this type, having spectra for ^{3}He distinctly more curved than for ^{4}He and thus having a ^{3}He/^{4}He ratio with a strong energy dependence, have been discussed by [8], [9].

From February 2007 through October 2008 (21 months), no clear increase in the ^{3}He intensity that would indicate a ^{3}He-rich event was detected by either of the STEREO/LET instruments. However, CIR events were common during this period and at times it would have been possible for a small ^{3}He-rich event with an energy spectrum not extending above a few MeV/nuc to be missed due to spillover from CIR ^{4}He.

B. The 4 November 2008 Event

The event of 4 November 2008 occurred when the STEREO spacecraft had separated from Earth by 41° in heliolongitude. The particles detected at 1 AU were associated with solar active region 11007, located at N35W38 as viewed from Earth. Solar observations [10] showed a C1 x-ray flare, type III radio bursts, and a small CME. The source region was nearly radially aligned with STEREO-A. The Parker spiral magnetic field calculated assuming a solar wind speed of 400 km/s would reach 1 AU approximately midway between STEREO-B and ACE. This connection is illustrated in the upper panel of Figure 2 where the dotted line shows the nominal field line and the light grey region shows a band extending $\pm 20^\circ$ about the nominal connection. This width corresponds approximately to the $\pm 1\sigma$ spread of heliolongitudes over which ^{3}He-rich events have been observed relative to their associated x-ray flare events [1], [2]. The light shaded region extends to $\pm 2\sigma$. Mason et al. [10] report that the potential field source surface (PFSS) model corresponding to the time of the 4 November 2008 event does not indicate the presence of open field lines connecting the active region to the ecliptic plane.

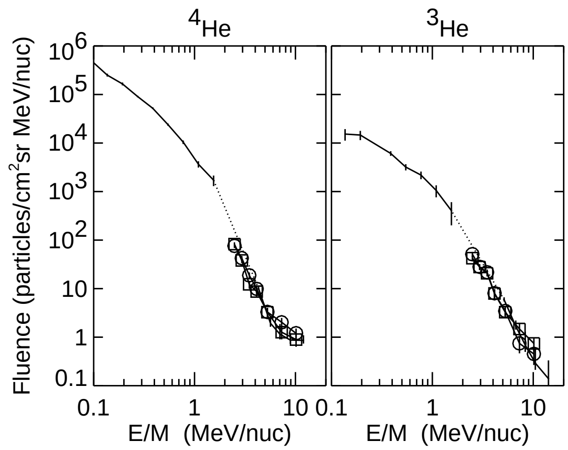

Fig. 1: Energy spectra of ^{4}He (left panel) and ^{3}He (right panel) measured in the ^{3}He-rich SEP event of 24 January 2007, when ACE and the two STEREO spacecraft were all located near Earth. Solid lines show spectra measured on ACE using ULEIS below 2 MeV/nuc and SIS at higher energies. Dotted lines connect the highest energy ULEIS point with the lowest energy SIS point. Open circles (open squares) show measurements from LET on STEREO-A (STEREO-B). At high energies the ^{3}He/^{4}He ratio is close to unity, but below 1 MeV/nuc ^{3}He has a harder spectrum than ^{4}He, resulting in a decrease of the ^{3}He/^{4}He ratio with decreasing energy. The flattening of the ^{4}He spectrum near 10 MeV/nuc is due to anomalous cosmic rays (ACRs).

The intensity versus time plots in Figure 2 show observations of electrons, He isotopes, and O and Fe ions from the three spacecraft. The energy ranges used, which have been chosen to match as closely as possible between STEREO and ACE, are listed in the figure caption. The observations of ^{4}He at STEREO-A were dominated by a CIR event at this time and have been omitted. Although the ion intensities are low, the SEP event is clearly seen from the increases in ^{3}He and in the Fe/O ratio at STEREO-B and ACE. At STEREO-A, however, the ^{3}He, O, and Fe intensities are near background levels with no indication of the SEP event. The observation of ion increases at locations $\sim 20^\circ$ ahead and behind the nominal connection to the active region is consistent with the previously-reported heliolongitude distribution [1], [2], as is the absence of a detection at STEREO-A with its $\sim 60^\circ$ separation from the nominal field line.

The electron data from STEREO-B and ACE show evidence for at least two distinct injections. At STEREO-A the electron event(s) are also observed, but with a distinctly slower rise to maximum and lower peak intensity than at STEREO-A. With the slower rise, multiple injections are not as clearly discernible.

C. Other Events

Two additional ^{3}He-rich events (29 April 2009 and possibly 6 November 2008) were detected by LET on STEREO-A, but were not observed at either ACE or STEREO-B. A few other events, including some reported in [10] and those that occurred during early May 2009, had ^{3}He intensities that were too low for the STEREO/LETs to detect and thus were not included in the present study.

III. DISCUSSION

In the 4 November 2008 event, energetic electrons were detected at all three spacecraft (Fig. 2), in spite of the large (82°) spread in heliolongitude. On the other hand, ions were detected only at STEREO-B and ACE, both within $\sim$20° from the nominal connection to the flare site, and not at STEREO-A, which had a connection angle of $\sim$60°. These results are consistent with the few previous multipoint studies of ^{3}He-rich events. Wibberenz & Cane [4] investigated electron events using data from Helios-1 & -2 and IMP-8 and found cases in which electrons were detected by spacecraft separated by 80° or more in longitude. Reames and collaborators [3] used the two Helios spacecraft plus ISEE-3 to search for events in which ^{3}He could be detected at two or three spacecraft, requiring similar ^{3}He/^{4}He ratios at the different spacecraft to confirm the association. They found only three events during 1979–1982 that met their criteria, and they concluded that it is typically possible to detect ions from ^{3}He-rich events only within $\sim$20° of the field line from the flare. (They did report one example [10 February 1979] in which an event may have been detected with three spacecraft spread over $\sim$60° in longitude and with one of the spacecraft possibly as far as 90° east of the flare site, but it was not possible to determine whether all three spacecraft observed consistent ^{3}He/^{4}He ratios in this event.) Reames et al. [3] concluded that the ion data are consistent with rather narrow longitudinal distributions for the ions. A direct comparison between electron and ion longitudinal distributions in the Helios events has not been reported; the lists of 3-spacecraft electron events from [4] and of 2- or 3-spacecraft ^{3}He events from [3] have no events in common.

In the present study it was possible to observe both electrons and ions from the same event at widely spaced longitudes. It is not clear whether the apparently different longitudinal extents of the ion and electron distributions is a characteristic feature of ^{3}He-rich events, as one might conclude from comparing the electron results of Wibberenz & Cane [4] with the ion measurements of Reames et al. [3], or if it might instead be due to instrument sensitivity limitations. A quantitatively-useful comparison of intensity–time profiles between electrons and ions is difficult because differences in particle speeds and rigidities can result in significant differences in interplanetary diffusion coefficients and adiabatic energy losses. However, we note that the peak electron intensity at STEREO-A is a factor $\sim$ 7 less than that at STEREO-B (see Fig. 2), and if the ^{3}He intensities at the two STEREOs differed by this same factor, the ^{3}He count rate in the STEREO-A LET would have been only marginally detectable in this event.

If one assumes that the lack of ion detections at STEREO-A in the 4 November 2008 event is actually due to the ions having a significantly narrower longitudinal distribution than the electrons, one can speculate about the possible mechanism responsible for this effect. There are several reported differences between SEP electrons and SEP ions from flare-associated events that could be related to such an effect. Observations of electron spectra extending smoothly down to energies of a few keV [11] in some events have been used to argue that electron acceleration must take place relatively high in the corona, since the overlying column density of matter in the low corona would prevent the escape of such low energy electrons. On the other hand, the increase in the ionic charge state of Fe at energies around 0.5 MeV/nuc [12] is thought to be due to stripping by Coulomb collisions. The relatively high density required to achieve the necessary stripping on the time scale of a flare event suggests a source in the low corona.

Another difference is found between the locations where hard x-rays and gamma-rays are emitted from a flare event on the Sun [13], [14]. The x-ray sources, which are produced by electrons interacting at footpoints of magnetic loops, are not collocated with the gamma-ray sources produced by interacting ions, indicating that the acceleration regions for electrons and ions are not identical. Thus it is possible that the two populations could be escaping into the heliosphere on different open field lines, which could lead to different longitudinal distributions. If, as suggested by our work and by the Helios studies [3], [4], the spread of longitudes for electrons is systematically broader than that for ions, these differences may provide significant constraints on the geometry involved in the reconnection and acceleration processes.

Wibberenz & Cane [4] suggest that the wide longitudinal extents of electron events could be the result of propagation in the low corona carrying the particles to open field lines remote from the flare site. They point out that the distance particles can be transported before escaping should depend inversely on the particle velocity and thus should be much more significant for electrons than for ions.

Multipoint measurements in additional ^{3}He-rich SEP events will be needed to determine 1) how far away in longitude from their solar sources electrons and ions from ^{3}He-rich events can be observed and 2) whether the longitudinal distributions of electrons and ions actually differ significantly from one another. With the

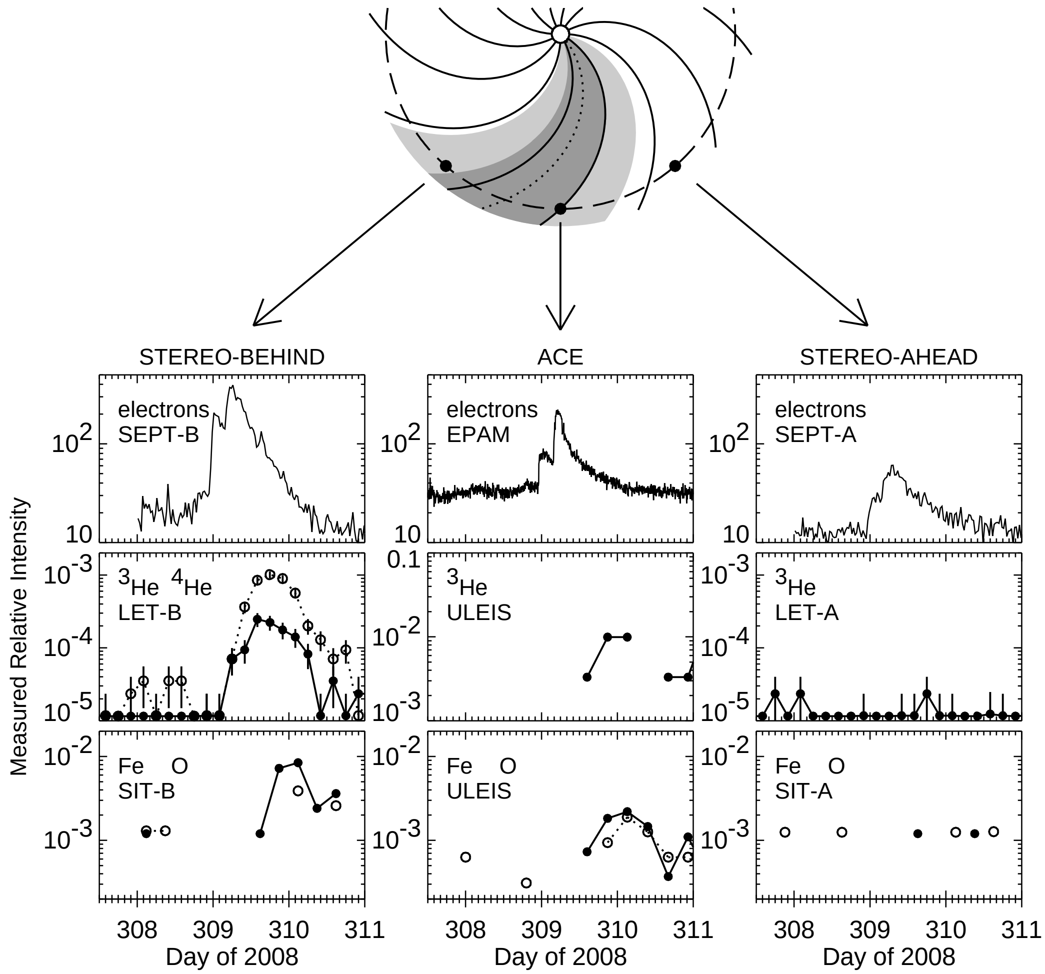

Fig. 2: Observations of solar energetic particles from the event(s) of 3–4 November 2008 (day of year 308–309). Left column: STEREO-BEHIND; center column, ACE; right column, STEREO-AHEAD. Upper row shows electrons from STEREO/SEPT (65–105 keV) and ACE/EPAM (62–103 keV). Middle row shows ^{3}He (filled circles and solid lines) and ^{4}He (open circles and dotted lines) from STEREO/LET (2.3–3.8 MeV/nuc) and ACE/ULEIS (0.32–0.45 MeV/nuc). Bottom row shows Fe (filled circles and solid lines) and O (open circles and dotted lines) from STEREO/SIT and ACE/ULEIS (0.32–0.45 MeV/nuc). The drawing indicates the locations of the three spacecraft in their 1 AU orbit (dashed line). The nominal Parker spiral field line (for $V_{\rm SW}$=400 km/s) from the flare site is shown as the dotted line. The dark and light shaded bands indicate spreads of $\pm 20^\circ$ and $\pm 40^\circ$, respectively, about the nominal field line.

expected increase in solar activity over the next year, the combination of ACE plus the two STEREO spacecraft is well positioned to search for events with particle detections far from the nominal connection to the flare site and to test the adequacy of present ideas about the escape of flare-accelerated particles from the Sun and their transport in the inner heliosphere.

Acknowledgments

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